Quality of Pellets Made from Agricultural and Forestry Crops in Costa Rican Tropical Climates

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Quality of Pellets Made from Agricultural and Forestry Crops in Costa Rican Tropical Climates

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Pellets may be produced with different types of agriculture or forestry crops in Costa Rica. This work evaluated the energy, physical, and mechanical properties of pellets fabricated from 12 types of agricultural and forestry crops (*Ananas cumosos*, *Arundo donax*, *Coffea arabica*, *Cupressus lusitanica*, empty fruit bunch and oil palm mesocarp fiber of the fruit of *Elaeis guineensis*, *Gynerium sagittatum*, *Pennisetum purpureum*, *Phyllostachys aurea*, *Saccharum officinarum*, *Sorghum bicolor*, and *Tectona grandis*), and similarities among these crops were established by multivariate principal component analysis. High variation was found in the pellet properties. The energy evaluation revealed that *C. lusitanica* and *P. aurea* are the crops with the best qualities for fuel use because of their high calorific values (from 16807 kJ/kg and 19919 kJ/kg, respectively) and low ash content (1.03% and 3.39%, respectively). As for physical properties, most crops exhibited values within the range noted by several authors and standards. All 12 pellet crops displayed high durability (from 72.12% to 92.98%) and compression force (from 295.18 N to 691.86 N). Moreover, the evaluation of crop similarities allowed the determination of four group combinations. Within these groups, *C. lusitanica*, *P. aurea*, and *G. sagittatum* had similar energy qualities and the best caloric characteristics.

Keywords: Biomass; Fuel; Pellet properties; Short-rotation crops; Mixture species

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INTRODUCTION

Environmental problems, increasing energy demands, and the decreasing availability of fossil fuels have stimulated the search for sustainable technologies based on renewable raw materials (Bringezu 2014). Biomass is one of the most promising energy sources, as it is an alternative to conventional energy sources such as oil and natural gas (Monteiro *et al.* 2012). One of its main advantages is that it is a clean and renewable product that contributes to reducing greenhouse gas emissions and dependency on fossil fuels (Monteiro *et al.* 2012; Daioglou *et al.* 2014). In this sense, the search for biomass from agricultural and forestry crops has advanced in the last few years (Hauk *et al.* 2014).

Nevertheless, the great amount of energy required to process biomass constitutes a limiting factor for its use, despite the fact that this energy requirement can be 70% less than what is required to process steel (Monteiro *et al.* 2012; Hauk *et al.* 2014). Its high moisture content, irregular shape and size, and low bulk density make it difficult to transport, store, and use in its original form (Hauk *et al.* 2014).

Conversion of biomass to pellets significantly reduces storage and transportation costs (Monteiro *et al.* 2012; Hughes *et al.* 2014). In addition, these pellets have higher density, are more homogeneous, and have greater energy potential (Dwivedi *et al.* 2014).

Currently, various raw materials are used to produce pellets in countries with temperate climates (Kuparinen *et al.* 2014). Many of these materials come from energy crops or industrial residues, mostly from the food industry. For example, some agricultural crops stand out in temperate climate regions, such as maize, sorghum, some potato varieties, and manioc, as well as short rotation forestry crops such as willow, pine, beech, and spruce (Shabani *et al.* 2013). In turn, a few agricultural and forestry crops have been used to manufacture pellets in tropical countries; some examples include coffee or forestry species like eucalyptus or tropical pines (Virmond *et al.* 2013; Lamers *et al.* 2014; Searle and Malins 2014).

There are a number of studies related to pellet characteristics and production involving species in temperate climates. These studies have focused on the following aspects: (i) the manufacturing process (Filbakk *et al.* 2011); (ii) improvement of conditions by means of additives or by treating the biomass before or after pellet manufacture, using roasting, for example; (iii) the evaluation of energy, physical, mechanical, and chemical aspects of pellet quality (Bergström *et al.* 2008); and (iv) pellet combustion and emission process evaluation (Abuelnuor *et al.* 2014).

In many small countries such as Costa Rica, pellets have gained popularity because some industries seek to switch from producing heat from fossil fuel sources to renewable sources to achieve carbon neutrality (Aragón *et al.* 2014). At present, for many tropical agricultural crops and forestry residues, the technological adaptations to the pellet production process (Aragón *et al.* 2014) and pellet quality evaluation are known (Tenorio *et al.* 2014); however, there is very limited information about the physical, chemical, or energy characterization of pellets produced from tropical crops in Costa Rica.

Therefore, the present work has the objective of evaluating pellet properties, taking into consideration energy (calorific value and combustibility index), physical properties (length, diameter, density, bulk density, and moisture absorption), mechanical properties (compression resistance and durability), and others parameter (ash, volatiles, and moisture content) of twelve agricultural and forestry crops (*Ananas cumosos*, *Arundo donax*, *Coffea arabica*, *Cupressus lusitanica*, empty fruit bunch and oil palm mesocarp fiber of the fruit of *Elaeis guineensis*, *Gynerium sagittatum*, *Pennisetum purpureum*, *Phyllostachys aurea*, *Saccharum officinarum*, *Sorghum bicolor*, and *Tectona grandis*) in Costa Rica. Finally, the similarities among these crops were established by multivariate principal component analysis.

EXPERIMENTAL

Materials

Twelve types of biomass from Costa Rican crops were selected to manufacture pellets; two were forestry species and ten were agricultural crops. The following three aspects were considered in this selection: their adaptability to the climatic and edaphic conditions of Costa Rica, an expected dry biomass production of over 20 ton/ha, and the possibility of pellet production throughout the year. Table 1 presents information regarding the 12 crops that were utilized.

Table 1. Description of 12 Crops used for Pellet Manufacture

Crops	Scientific name	Origin	Abbreviation
Pineapple leaves	*Ananas cumosos*	Buenos Aires, Puntarenas	PLP
Giant cane	*Arundo donax*	Filadelfia, Guanacaste	AD
Coffee pulp	*Coffea arabica*	Tarrazú, San José	CA
Sawlog residuals	*Cupressus lusitanica*	Agua Caliente, Cartago	CL
Empty fruit bunch of the oil palm	*Elaeis guineensis*	Parrita, Puntarenas	EFB
Oil palm mesocarp fiber of the fruit	*Elaeis guineensis*	Parrita, Puntarenas	OPMF
Wild cane	*Gynerium sagittatum*	Río Frío, Limón	GS
King grass	*Pennisetum purpureum*	Paraíso, Cartago	PP
Golden bamboo	*Phyllostachys aurea*	Cartago, Cartago	PA
Sugarcane	*Saccharum officinarum*	San Carlos, Alajuela	SO
Sorghum	*Sorghum bicolor*	Upala, Alajuela	SB
Sawlog residuals	*Tectona grandis*	Abangares, Guanacaste	TG

Methods

Pellet manufacturing process

The pellet manufacturing process was carried out at Pelletics S.A. (http://pelletics.com/), located in San Carlos in Alajuela province (Costa Rica). Aragón *et al*. (2014) detailed the pellet manufacturing process from the moment the crops enter the plant to the pelletizing process.

The manufacture of pellets from CL, GS, PA, and TG used the following equipment and procedures. The material was chipped in a JENZ chipper, model AZ 50 (Germany), and the milling was performed using a KAHL fixed ring matrix with holes 15 mm in diameter (Germany). Afterwards, the granulate material was dried to reach 8% to 14% moisture content using a rotary drum (12 m long x 3 m diameter), and air-heated to 400 °C. Finally, the pelletizing process was performed in a KAHL machine, model 35780, consisting of a fixed ring matrix that was 780 mm in diameter, containing holes 6 mm in diameter and 30 mm long, with three rotating rollers; a temperature of 120 °C was reached during the process.

The process was adjusted for the remaining species through additional stages. The adjustments were as follows: (i) For the PLP, SO, AD, and SB crops, the chipper illustrated in Fig. 1 used in the production system did not function adequately; thus, specialized machinery that can process other types of biomass, specifically sugarcane mills or chippers, were required; (ii) For the AD and PP crops, pre-drying was carried out to reach the optimum moisture for the chipping process. Pre-drying consisted of leaving the cut stems in the field for a three-day period; the semi-dry material was then taken through the chipping process; (iii) The EFB, OPMF, and CA did not need to be chipped and were taken directly to the milling stage; this material was collected from processing centers, and its moisture was similar to that of wood; and (iv) Once SB and SO were milled, a biomass pre-treatment was performed that consisted of extracting water using a solid separating press.

Determination of energy properties and ash content, volatiles, and moisture content

The properties determined included net caloric value (NCV), ash content, moisture content (MC), percent volatiles, and fuel value index (FVI). The NCV was determined in the absence of water (0% moisture content) using Parr's calorimetric test in accordance with the ASTM D-5865 04 (2003) standard. To determine the ash content, 10 randomly selected 2 g pellet samples were used and the ASTM 1102-84 (2013a) standard procedure was followed. The pellets' MC was determined using a moisture scale, model MB45, made by OHAUS (USA), which determines moisture with respect to initial weight. For the percent volatiles, 10 pellet samples of 3 g each were used, and the ASTM D1762-84 (2013b) standard was followed. The FVI was calculated using the NCV, density, and ash content, based on the methodology proposed by Purohit and Nautiyal (1987). Ten pellets with an approximate weight of 0.60 g each were randomly selected among the pellets manufactured for each property.

Determination of physical properties

The physical properties determined were the pellets' length, diameter, moisture absorption percentage, and bulk density. To determine length, diameter, and moisture absorption, a representative random sample of 30 pellets *per* crop was used. To determine moisture absorption, pellets were placed in a desiccator containing a saturated solution of potassium nitrate at 22 °C (21% equilibrium moisture content); pellets were weighed on a weekly basis until they reached constant weight. Samples were weighed before and after this period. The absorption percentage was calculated with Eq. 1:

$$Moisture\ absorption\ (\%) = \frac{weight\ at\ 21\%(g) - initial\ weight(g)}{initial\ weight\ (g)} * 100 \qquad (1)$$

To determine the apparent density, small quantities of pellets were slowly added to a beaker, filling it up to its 500-mL capacity. Then, the weight of pellets occupying this space was determined. The apparent density was determined by the ratio between the weight and the volume occupied by the pellets. Ten pellets were randomly selected from the total crop set, and the length and diameter were measured with a calibrator. Lastly, their mass was calculated on an analytical balance. The pellets' bulk density can be obtained using Eq. 2:

$$Pellet\ bulk\ density\ \left(\frac{g}{cm^3}\right) = \frac{pellet\ mass\ (g)}{pellet\ volume\ (cm^3)} \qquad (2)$$

Determination of mechanical properties

Pellet mechanical durability and compression resistance were determined. The DD CENT/TS 15210-1 (2005) standard was used to calculate mechanical durability. For this test, 10 representative pellet samples of 500 g each were sifted through a sieve with an aperture of 3.36 mm to eliminate fine particles. Then, the sifted samples were placed in equipment proposed by the standard, which was fabricated for this purpose, at a speed of 50 rpm for 10 min. Later, the samples were removed, sifted once more, and weighed.

For the compression resistance test, 10 pellets with an approximate length of 13 mm were randomly selected. The test was performed longitudinally on the pellet according to the methodology proposed by Aarseth and Prestlokken (2003) using a Tinus Olsen (USA) universal test machine, model H10KT, with a capacity of 1 ton. For this test, a compression charge speed of 0.02 mm/s was applied. This test determines the pellet's force at break *vs*. deformation measurements. The pellet's force at break was reported.

Statistical analysis

A descriptive analysis was performed (median, standard deviation, and maximum and minimum values) for the following variables: pellet length and diameter, NCV, ash content, percent volatiles, MC, FVI, apparent density, bulk density, absorption percentage, durability, and force at break. In addition, it was determined whether variables complied with the premises of normal distribution, homogeneity of variances, as well as the presence of extreme values. A variance analysis was applied to verify the existence of significant differences among the averages of the variables ($P<0.05$). Tukey's test was carried out to determine the statistical differences among crops, for the mean value of each of the abovementioned values.

Finally, a multivariate principal component analysis was used among biomass crops and all evaluated energy, physical, and mechanical properties. Multivariate principal component analysis is appropriate when data have been obtained for a number of observed variables; a smaller number of artificial variables (called principal components) that will account for most of the variance in the observed variables can be obtained. The principal components may then be used as predictor or criterion variables in subsequent analyses (Johnson and Wichern 1992). Also, from the principal components, two fist components were selected and were interpreted according to properties correlated with these components. In addition, multivariate analysis provided Eigenvalues, a scale associated with a given linear transformation of a vector space provided to each property evaluated.

RESULTS

Energy, Physical, and Mechanical Properties

Table 2 shows the energy properties of the 12 different crops for pellet manufacture. The NCV varied from 11,616 kJ/kg to 19,919 kJ/kg, and four groupings were created based on the statistical differences in the energy properties: (i) PA and GS, with the highest values, (ii) followed by PP, SB, CL, AD, and, OPMF, (iii) then by TG and EFB, and lastly (iv) the group with the lowest values, composed of CA, SO, and PLP. The values obtained for ash content ranged from 1.0% to 10.5%, and five groupings were formed: (i) AD, with the highest value, (ii) followed by PP, CA, SO, and OPMF, (iii) another group formed by PLP, EFB, SB, and GS, (iv) another group formed by PA and TG, and (v) CL. The percent volatiles for the 12 crops varied between 69.2% and 78.0%, and the crops were grouped into four categories: (i) SO and CL, presenting the highest values, (ii) followed by TG, PA, and GS, (iii) PLP, SB, OPMF, and EFB, and (iv) one last group, formed by AD, CA, and PP, which represent the lowest ash percentage values. The FVI test determined that CL had the highest FVI, followed by PA; the remaining crops (PLP, EFB, OPMF, CA, GS, PP, SO, SB, and TG) had statistically similar FVI values, while AD had the lowest value. Pellet MC for the 12 crops varied from 6.7% to 12.6%, and once more four groups were established: (i) crops with the highest MC were SB, PP, TG, and AD, (ii) followed by PLP and CA, (iii) then by SO, OPMF, and EFB, and lastly (iv) CL and PA, with the lowest values.

Table 2. Energy Properties of 12 Pellets Crops from Costa Rica

Crops	Net caloric value (kJ/kg)	Ash content (%)	Volatile content (%)	Moisture content (%)	Fuel value index
A. cumosos (PLP)	11,617 (3.6)^{E}	6.1 (30.7)^{CD}	73.1 (1.3)^{C}	10.9 (3.3)^{B}	242 (46.1)^{CD}
A. donax (AD)	15,930 (4.0)^{BC}	10.5 (4.6)^{A}	70.5 (0.9)^{DE}	12.0 (4.7)^{A}	163 (6.1)^{D}
C. arabica (CA)	12,249 (4.0)^{E}	6.7 (8.8)^{BC}	70.0 (0.8)^{E}	10.1 (3.3)^{BC}	232 (12.4)^{CD}
C. lusitanica (CL)	16,807 (7.9)^{B}	1.0 (28.0)^{F}	76.7 (0.2)^{AB}	7.5 (16.3)^{E}	2803 (25.7)^{A}
E. guineensis (EFB)	14,182 (9.7)^{D}	5.7 (12.7)^{CD}	71.7 (0.1)^{CD}	9.0 (6.9)^{D}	349 (15.0)^{CD}
E. guineensis (OPMF)	15,831 (5.7)^{BC}	6.2 (20.9)^{BC}	72.4 (0.8)^{C}	9.2 (5.1)^{CD}	340 (18.6)^{CD}
G. sagittatum (GS)	18,750 (9.9)^{A}	4.9 (7.5)^{D}	75.1 (0.3)^{B}	9.7 (6.2)^{CD}	491 (17.4)^{C}
P. purpureum (PP)	16,979 (3.7)^{B}	7.5 (4.3)^{B}	69.2 (1.6)^{E}	12.1 (3.8)^{A}	244 (4.0)^{CD}
P. aurea (PA)	19,919 (7.2)^{A}	3.4 (13.9)^{E}	75.3 (0.7)^{B}	6.7 (5.9)^{E}	1039 (10.1)^{B}
S. officinarum (SO)	12,146 (2.9)^{E}	6.6 (17.6)^{BC}	78.0 (0.1)^{A}	9.7 (9.1)^{CD}	212 (12.8)^{CD}
S. bicolor (SB)	16,906 (5.6)^{B}	5.5 (3.0)^{CD}	72.6 (0.9)^{C}	12.6 (5.6)^{A}	273 (9.7)^{CD}
T. grandis (TG)	15,261 (2.3)^{CD}	3.2 (24.1)^{E}	75.9 (0.1)^{B}	12.1 (3.7)^{A}	463 (19.5)^{CD}

Values in parentheses are the variation coefficients (average*100/standard deviation)
Different letters for each parameter represent statistical differences between crops (significances at 95%)

Regarding the physical properties (Table 3), it was found that pellet length varied from 12.3 to 27.7 mm. *G. sagittatum*, CL, and CA had the longest pellets, while AD pellets had the lowest values. For the remaining crops (PLP, EFB, OPMF, PA, PP, SO, SB, and TG), pellet length varied between 15.4 and 22.9 mm. In turn, pellet diameter varied from 5.9 mm to 6.6 mm. The following five crop groupings were created based on pellet diameter: (i) SO, with the greatest diameter (6.6 mm), (ii) followed by GS, SB, PLP, and TG, (iii) then by CL, PP, and OPMF, (iv) another group formed by EFB, AD, and CA, and finally (v) PA.

Table 3. Physical Properties of 12 Pellets Crops from Costa Rica

Crops	Length (mm)	Diameter (mm)	Moisture absorption (%)	Apparent density (kg/m^3)	Density (g/cm^3)
A. cumosos (PLP)	15.4 (16.6)^{FG}	6.2 (1.9)^{BC}	8.9 (22.4)^{AB}	-	1.23 (2.3)^{AE}
A. donax (AD)	12.3 (38.4)^{G}	6.1 (0.6)^{E}	9.7 (15.3)^{A}	456 (3.0)^{F}	1.29 (3.6)^{A}
C. arabica (CA)	24.8 (14.7)^{AB}	6.07 (2.0)^{E}	8.1 (53.6)^{BC}	595 (2.1)^{A}	1.28 (3.0)^{AC}
C. lusitanica (CL)	27.3 (18.4)^{A}	6.2 (1.2)^{CDE}	9.3 (13.7)^{AB}	549 (3.4)^{C}	1.21 (7.2)^{AEF}
E. guineensis (EFB)	22.9 (9.6)^{BC}	6.1 (2.0)^{DE}	5.1 (24.9)^{F}	575 (1.53)^{B}	1.23 (3.7)^{AD}
E. guineensis (OPMF)	17.3 (26.7)^{EF}	6.1 (4.1)^{CDE}	5.7 (14.7)^{DEF}	596 (1.6)^{A}	1.19 (7.1)^{BCDE}
G. sagittatum (GS)	27.7 (9.1)^{A}	6.3 (1.3)^{B}	5.7 (15.3)^{DEF}	542 (1.5)^{CD}	1.23 (2.2)^{AD}
P. purpureum (PP)	18.2 (32.5)^{DEF}	6.1 (1.9)^{CDE}	5.3 (7.6)^{EF}	524 (3.0)^{D}	1.29 (2.3)^{A}
P. aurea (PA)	21.0 (12.0)^{CD}	5.9 (4.9)^{F}	6.9 (16.5)^{CD}	490 (1.4)^{E}	1.17 (4.4)^{BDEG}
S. officinarum (SO)	18.4 (16.8)^{DEF}	6.6 (3.3)^{A}	5.7 (13.2)^{DEF}	500 (4.2)^{E}	1.10 (8.5)^{G}
S. bicolor (SB)	16.8 (26.1)^{EF}	6.3 (1.7)^{BC}	6.6 (11.2)^{DE}	386 (2.2)^{G}	1.13 (5.1)^{BFG}
T. grandis (TG)	19.8 (12.6)^{CDE}	6.2 (2.9)^{BC}	5.5 (19.2)^{DEF}	378 (3.7)^{G}	1.14 (4.7)^{BEG}

Values within parentheses are the variation coefficients (average*100/standard deviation)
Different letters for each parameter represent statistical differences between crops (significance at 95%)
There was not enough material for testing the bulk density with PLP

The percentage of moisture absorption varied from 5.1% to 9.7%, with four groupings: (i) AD, CL, PLP, and CA were the crops with the highest moisture absorption, (ii) followed by PA and SB, (iii) then by SO, GS, OPMF, TG, and PP, and finally (iv) EFB had the lowest moisture absorption percentage. The apparent density ranged from 386 to 596 kg/m^3; in this case, it was not possible to make any groupings because of the large statistical differences among the crops. Therefore, OPMF and CA presented the highest values, SB had the lowest value (386 kg/m^3), and the remaining crops (PLP, AD, CL, EFB, GS, PP, PA, SO, and TG) had apparent densities ranging from 456 to 575 kg/m^3. The bulk density of pellets varied from 1.10 to 1.29 g/cm^3 for all crops; PP, AD, CA, GS, EFB, PLP, and CL presented the highest values (between 1.21 and 1.29 g/cm^3), SO had the lowest value (1.10 g/cm^3), and the remaining crops (OPMF, PA, TG, and SB) had values between 1.13 and 1.19 g/cm^3.

Figure 1 shows pellets mechanical durability and force at break. For mechanical durability, AD, EFB, OPMF, PP, and TG possessed the highest durability percentages (92.% to 93%), followed by PLP and SO, with 90% and 91% respectively, while the rest of the crops (CL, SB, GS, and CA) showed values between 76% and 88%. Lastly, PA had the lowest durability, with a value of 72% (Fig. 1a). The force at break varied from 295 to 692 N, and the differences found among the medians permit three groupings: (i) PP, GS, and CL were the crops with the highest values, at 571, 634, and 692 N, respectively, (ii) CA, AD, EFB, and OPMF had intermediate values, between 416 and 485 N, and (iii) SO, PA, SB, TG, and PLP had the lowest force at break, ranging from 295 to 375 N (Fig. 1b).

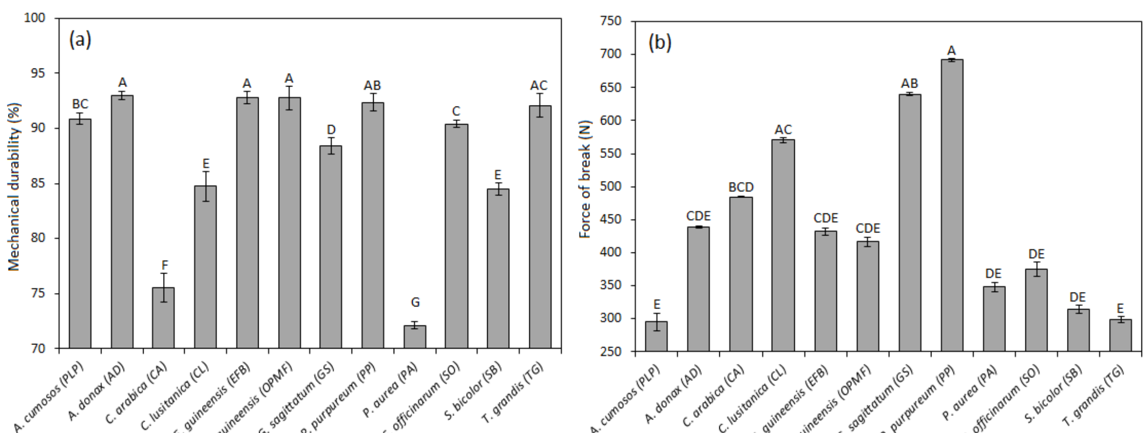

Fig. 1. (a) Mechanical durability and (b) force at break of 12 pellet crops in Costa Rica. Legend: Different letters for each crop represent statistical difference between crops (significances at 95%)

Figure 2 illustrates the behavior of one representative pellet for each crop in the force *vs*. deformation curve, according to three groups established in force to breakage: (i) PP, GS, and CL tended to reach high force levels (superior to 650 N) at low deformation values and present curves with steep slopes in the elastic area of the pellet; (ii) EFB, OPMF, and AD behaved differently; at the same deformation levels, the force they could withstand was lower (within the range of 500 N); and (iii) PA, SB, TG, PLP, and CA possess lower forces than those of the other groups at the same deformation values. In addition, their curve slopes were lower in relation to the other species. In contrast, SO presents a different case because its pellets were found to withhold forces superior to 500 N, which is the reason for placing it among species of the second group. Nevertheless, the deformation values of

0.2 or 0.4 mm exhibited breaking forces within the range of crops from the third group; in any case, the crop's slope was similar to the crops of the second group (Fig. 2).

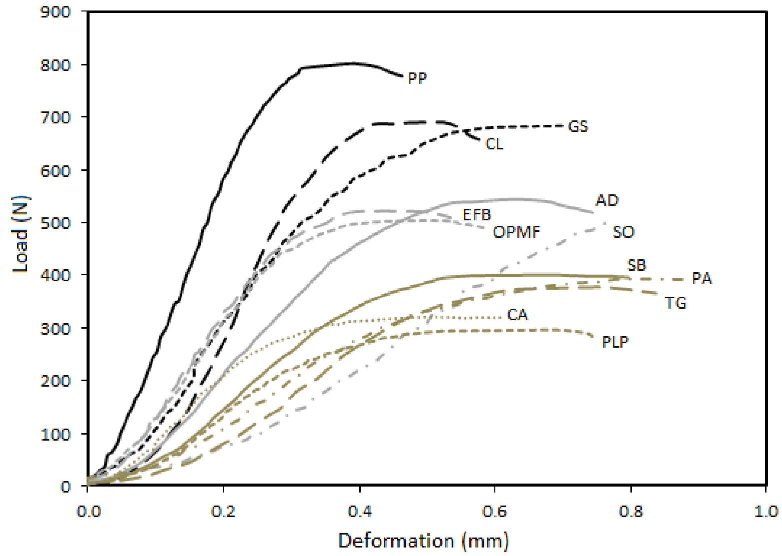

Fig. 2. Force *vs*. deformation for 12 pellet crops from Costa Rica

Multivariate Analysis

The multivariate principal component analysis (Table 4) of the physical, mechanical, and energy properties of the crops revealed that the first two principal

Table 4. Correlation Matrix of Multivariate Analysis for All Parameters Evaluated

Parameter	Factor 1	Factor 2
Moisture absorption	-0.26	-0.27
Length	-0.78**	0.01
Diameter	0.27	0.44
Calorific value	-0.46	-0.10
Moisture content	0.80**	-0.15
Ash content	0.76**	-0.53
Volatiles	-0.41	0.80
FVI	-0.87**	0.12
Apparent density	-0.05	-0.97**
Bulk density	-0.41	-0.50
Mechanical durability	0.47	-0.14
Force of break	-0.38	-0.72**
Compression strength	-0.53	-0.50
Eigenvalue	3.91	3.23
% Total	30.07	24.88
Eigenvalue cumulative	3.91	7.14
Total cumulative	30.07	54.95

**Parameter of pellet that affect statistically at 99%.

components could explain 55% of the variations of the pellet properties, which were considered in this study. Thirty percent of the data variations could be explained by Factor 1, where FVI, MC, pellet length, and ash percentage showed statistically significant effects on this factor, for which pellet length and FVI were negatively correlated and MC and ash content were positively correlated (Table 4). Similarly, Factor 2 explained 25% of the data variations of all pellet parameters, and it was negatively affected by apparent density and force at break (Table 4).

Multivariate analysis provided Eigenvalues for each principal component. The eigenvalues are a scale associated with a given linear transformation of a vector space provided to each parameter evaluated. If a scatterplot is created for the Eigenvector of each principal component in each of the crops analyzed (Fig. 3), one can observe four groups for the physical, mechanical, and energy properties: the first group is composed of CL, PA, and GS; the second group is formed by TG, SO, and SB; the third group is composed of OPMF, EFB, and CA; and the last group is composed of PP and AD.

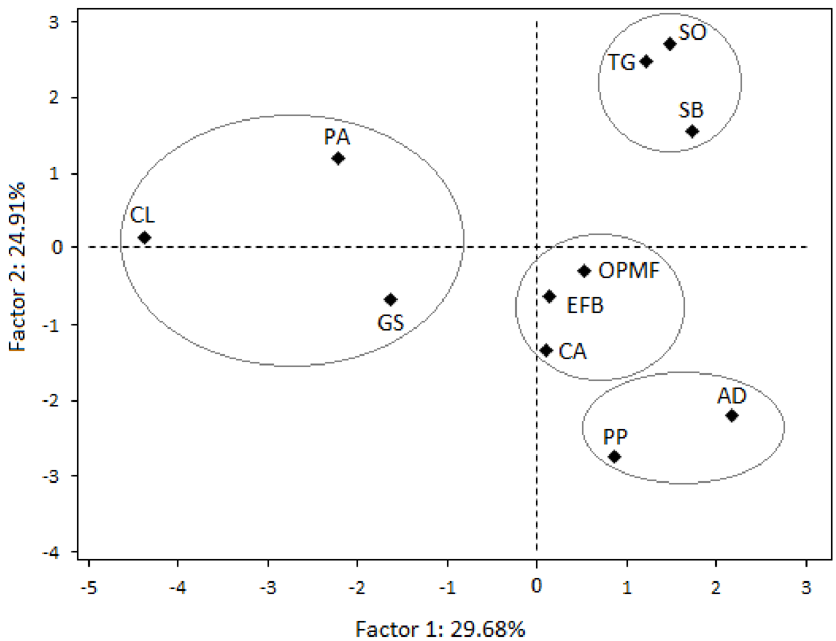

Fig. 3. Relationship of Eigenvectors of Factors 1 and 2 from the multivariate analysis of the physical, mechanical, and energy properties of species tested

ANALYSIS

Energy Properties

The NCV values varied from 11,616 to 19,919 kJ/kg (Table 2). The caloric values agree with those reported for fast-growing timber species in Costa Rica, which vary from 16,500 to 20,600 kJ/kg (Moya and Tenorio 2013). *T. grandis*, PLP, EFB, OPMF, AD, CA, and SO had values inferior to those for timber species, which probably makes them less recommendable as an alternative fuel compared to fast-growing timber species. Although there are many standards being used in European countries, they are irregular, but the German and Swiss standards are more developed and more effective for pellet characterization (Garcia-Maraver *et al.* 2011); thus they are considered in the study for comparison. The German standard (DIN 1996) recommends an NCV range for fuel material from 17,500 to 19,500 kJ/kg. Of the crops evaluated, only pellets from PA and GS fulfilled these recommendations. Based on the Swedish standard (SS 1998), which is less restrictive, all species can be commercialized in the Swedish marked. PA, SB, PP, and GS are grouped in Group 1 (NCV > 16, 890 kJ/kg); AD, CL, OPMF and TG are grouped in Group 2 (NCV varying from 15,100 to 16,890 kJ/kg), and other species are grouped in Group 3, because their values are lower than 15,100 to 16,890 kJ/kg. On the other hand, the European standards (CEN/TS 2004) are insufficiently restrictive because the heating value should be established by the owner manufacturer.

In relation to ash content, variation among crops was high, from 1.0% to 10.5%, and when comparing these values with those reported for timber species in Costa Rica (between 0.2% and 4.0%) by Moya and Tenorio (2013), it was observed that only CL, TG, and PA had ash content within the range of these species. Similarly, the ash content values obtained in this study according to ASTM D-1102-84 (2013a) did not comply with the permitted 0.5% limit according to the DIN 51731 (1996) standard or 1.5% permitted by Swedish standard (SS 1998). Another important aspect to consider in relation to the high ash content values (over 4%) is that a high ash percentage may lead to the corrosion of burners or boilers and abrasion of equipment (Mande 2009).

The percent volatiles variation in this study was between 69.24% and 77.96% (Table 2), which are higher values than those presented by Kataki and Konwer (2002) for timber species from Northeast India, which ranged from 13.5% to 40.1%. According to several authors, a high volatiles percentage produces more heat during combustion, which makes a material burn faster, making it less desirable as fuel (Jain 1994; Kataki and Konwer 2002).

There are different viewpoints concerning the MC that pellets should possess for good performance; normally, pellets contain a MC between 8% and 12% (Lehtikangas 2001; Kaliyan and Morey 2009). The MC of pellets manufactured in this study was between 6% and 12%, and crops such as CL and PA have a MC inferior to 8% (Table 2). However, according to several authors, high MC tends to decrease the energy potential of timber species (Jain 1994; Kataki and Konwer 2002). In the case of pellets, Telmo and Lousada (2011) point out that pellet NCV may double if pellets are completely dry. The German standard (DIN 1996) recommends an MC less than 12%, then MC of almost pellet fulfils of German standard, except PP and SB, which are in border of this range. Meanwhile, CL, EFB, OPMF, GS, PA, and SO fulfill the Swish standard (SS, 1998). On the other hand, European standards (CEN/TS 2004) establish ranges of variation for MC, such that all pellets species can be grouped in some of these ranges.

The FVI values for the 12 crops varied from 163 to 2803 (Table 2). When comparing these values to those reported by Moya and Tenorio (2013) for solid wood in Costa Rica, PLP, AD, PP, SB, CA, and SO possessed lower FVI than the range (from 337 to 6390) indicated by these authors; hence, they are less recommendable for fuel use in comparison with timber species. The FVI value is one of the best parameters for determining how desirable a species can be as fuel, mostly because it takes into account NCV and density as positive factors and ash content and MC as negative factors (Purohit and Nautiyal 1987; Jain 1992). Their FVI values suggest that CL and PA are the crops with the best properties for fuel use and therefore for pellet manufacture.

The NCV variations observed in the 12 crops (Table 2) can be explained by the variations in chemical properties for each biomass type, such as ash content, volatile substances, extractives, and fixed carbon (Gominho *et al.* 2012; Moya and Tenorio 2013). According to several authors, the ash content and volatiles directly affect the energy conversion process and specifically decrease the NCV (Kataki and Konwar 2002; Kumar *et al.* 2009; Gominho *et al.* 2012). Even so, the correlation index indicates weak relationships between NCV and both ash content and volatiles (Figs. 4a and 4b), which could mean that NCV variations between crops could be the result of other chemical properties that were not evaluated in this study. For example, high extractives content and fixed carbon in biomass may influence the NCV (Kataki and Konwer 2001; Moya and Tenorio 2013).

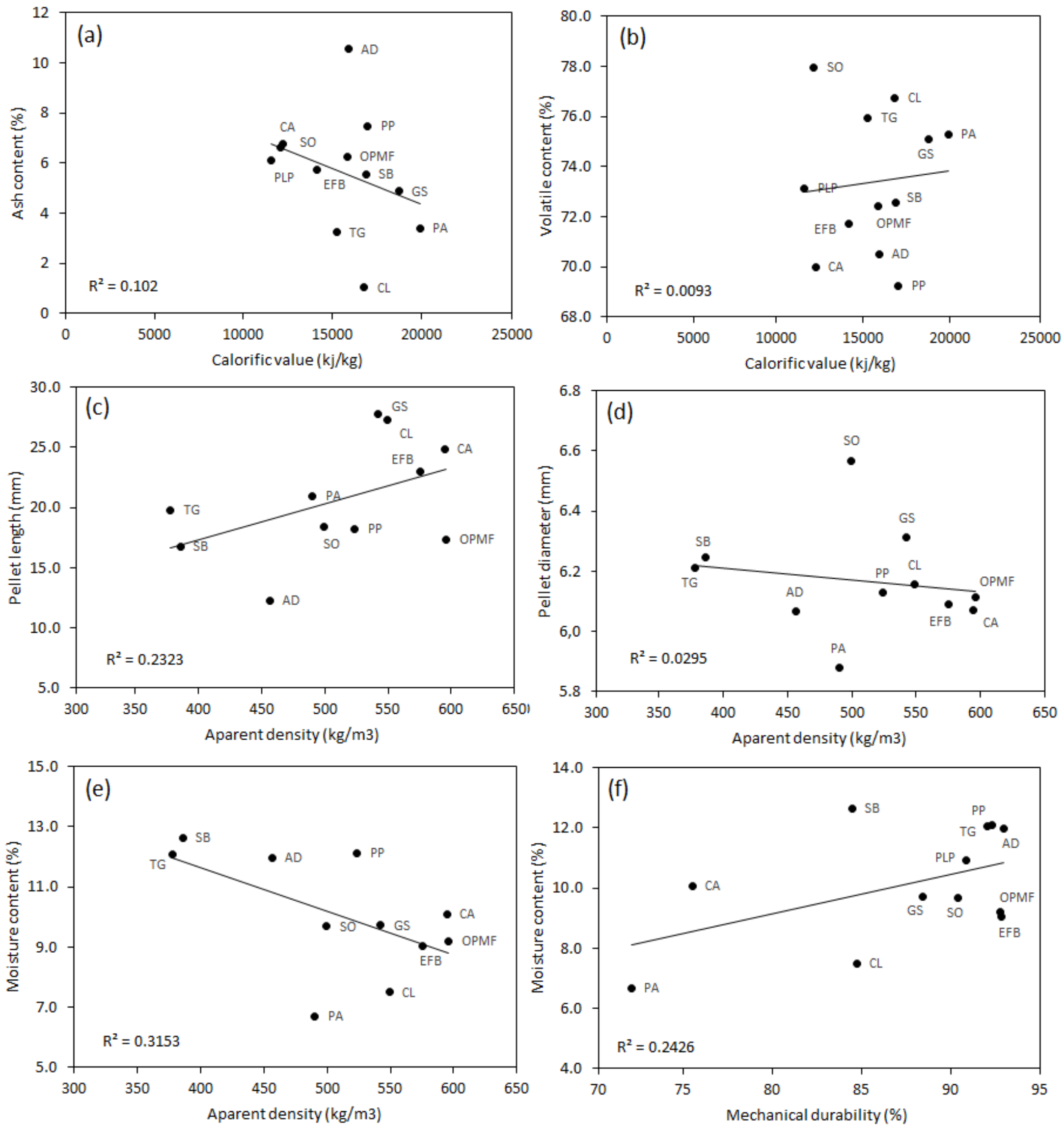

Fig. 4. Relationship between net caloric value (NCV) and different parameters measured in the pellet for 12 species tested.

Physical Properties

Faseina (2008), in a study performed on peanut hull pellets, points out that the optimum moisture absorption point for pellets is from 3% to 5% and that an additional increase in absorbed moisture could result in decreasing the quality and strength characteristics of pellets. The absorption capacity obtained in this case for the 12 crops ranged from 5.1% to 9.7%, higher values than those of the abovementioned study. Pellets produced with these crops could present moisture absorption problems and thus strength-related problems.

The values obtained for apparent density (Table 3) show that, for CA, OPMF, EFB, CL, GS, PP, SO, and PA, the apparent density values were compatible with those found in pellets manufactured from maize, wheat, and sorghum residues, where variation was from 479 to 649 kg/m^3 (Theerarattananoon *et al.* 2011). However, values obtained for TG, SB, and AD (Table 3) were inferior to the ones mentioned by these authors. Low bulk density values have an effect on transportation costs because the energy value *per* unit volume is lower (Theerarattananoon *et al.* 2011). The average bulk density obtained for the pellets of the 12 crops varied from 1.10 to 1.29 g/cm^3 (Table 3). Such density values can be found within the range suggested by DIN 51731 (1996) and Swish standard (SS 1998), which varied from 1.0 to 1.4 g/cm^3. But European standards (CEN/TS 2004) are insufficiently restrictive, because the bulk density value should be established by the owner manufacturer.

Variations in the physical properties of pellets (Table 3) may be clarified from two angles: factors related to the material and factors related to the process. For water absorption capacity, variations among species can be attributed to variations in pellets' MC. Pellets with high MC tend to absorb less water, while pellets with low MC tend to absorb more water. This behavior was found in SB, PP, and TG crops, which had low absorption values and high MC (Tables 2 and 3). The differences among the bulk densities of the 12 crops may be explained by variations in size (pellet length and diameter). Figure 4c and 4d show the correlations between pellet length, diameter, and apparent density. The apparent density increases with increasing pellet length, but with respect to the diameter, no correlation with the apparent density is observed. Another aspect that influences apparent density variations is MC. Several authors have suggested that an increase in pellet MC results in a linear decrease in apparent density (Mani *et al.* 2006; Fascina 2008); such a correlation was found in the crops studied (Fig. 4e), but this correlation was low (R^2=0.32).

The bulk density variations between crops may be caused by the internal structure of each of the analyzed crops, as well as the temperature and pressure applied during the pelletizing process (Rhén *et al.* 2005; Mani *et al.* 2006). Gilbert *et al.* (2009) indicated that at temperatures between 14 and 50 °C, the density increases substantially, while at higher temperatures, between 75 and 95 °C, pellets tend to maintain a stable density. Several authors indicate an existing relationship between pressure and density, where density increases exponentially with an increase in pelletizing pressure, until reaching a point of maximum density (Husain *et al.* 2002; Rhén *et al.* 2005).

Mechanical Properties

Durability is defined as the capacity of pellets to sustain destructive loads and forces during transportation (Tabil and Sokhansanj 1996), so it is of utmost importance to have adequate values for this parameter; Colley *et al.* (2006) suggest the following three categories: (i) acceptable, when the durability is greater than 80%, (ii) average, when durability varies between 70% and 80%, and (iii) low, when the parameter is lower than 70%. When applying these categories to the durability values obtained for the pellets of the 12 crops, one can confirm that the majority of crops (CL, TG, PLP, EFB, OPMF, AD, GS, PP, SB, and SO) exhibited acceptable durability, with values greater than 80%. Meanwhile, PA and CA showed average durability (Fig. 1a), and no crops were found to have low durability. The categories obtained for the crops evaluated (acceptable and average) suggest that pellets will perform well, as according to Temmerman *et al.* (2006). The values obtained in durability did not fulfill to DIN (DIN 1996) or Swish standard (SS 1998). But European standards (CEN/TS 2004) are not restrictive enough because the durability value is greater than 90%; thus, many species (PLP, AD, EFB, OPMF, PP, SO and TG) fulfill this standard.

The differences in durability among crops (Fig. 1a) can be focused by considering MC and particle size. Durability has been reported to increase with an increase in MC (Colley *et al.* 2006; Filbakk *et al.* 2011), and pellets from the 12 crops evaluated were observed to have a similar behavior (Fig. 4f), however a low R^2 value was observed, which means that the durability cannot be explained solely on the basis of variations in MC. With respect to particle size, generally more durable pellets are produced when working with fine particles (Mani *et al.* 2006; Serrano *et al.* 2011). Although in this present study particle size was not determined, as was mentioned before, the methodology used to manufacture pellets was different for some crops (PLP, SO, AD, SB, PP, OPMF, and CA). This could have caused different particle sizes among crops and low particle uniformity, which would affect their durability.

The force at break values found in this study (Fig. 1b) were superior to those obtained by García-Maraver *et al.* (2010) for pellets made from olive tree branches. It may be inferred from this comparison that having an adequate force at break value allows pellets to maintain their shape during transportation (Kaliyan and Morey 2009). To explain the differences found in force at break of the different crops (Fig. 1b), several studies suggest that the pellet production stages, such as drying at high temperatures, milling, and pressing, along with the MC of the materials, affect the final strength properties of pellets (Rhén *et al.* 2005; Gilbert *et al.* 2009; Serrano *et al.* 2011). In this study, the pelletizing process was the same for all crops; however, because of the properties of each crop, there could have been temperature and pressure variations during the pelletizing process, different to those referenced, which could affect pellet compression resistance, lowering their force at break. As for moisture, the MC of the material before pelletizing should be close to 10%. Nevertheless, it was not possible to obtain this moisture level in the present study for the crop pellets evaluated, as MC varied from 6.7% to 12.6%. Also some studies have pointed out that the compression strength increases with decreasing MC (Rhén *et al.* 2005). Still, for this study, it was not possible to prove this, as crops with high MC also possessed high force at break values. For example, PP had the highest force at break, of 692 N, but it also had one of the highest MC among the pellets of the crops evaluated (12.1%) (Table 2).

Multivariate Analysis

When evaluating the similarity among crops considering all pellet properties, the multivariate principal component analysis showed that a high percentage of variation was focused on two factors: the first factor is related to the energy capacity of pellets, because it is related to FVI, MC, and ash content (Table 4), while the second factor is related to their strength and presents a correlation with density and force at break during compression (Table 4). This permitted the groupings detailed in Fig. 3. Such a relationship allows these crops to be combined without altering the thermic behavior of the equipment where pellets are being used. For example, no behavioral changes are likely to be expected in a burner when CL, PA, or GS pellets are used, which form a set of species having similar thermic conditions. This means that, when pellet supplies are scarce, adding or mixing pellets of another crop could occur without altering the thermic or structural behavior.

Likewise, the groupings obtained through multivariate principal component analysis will make it possible to establish cultivating policies for these crops. For example, a company wishing to standardize the raw material utilized to manufacture pellets of similar conditions could establish a policy of cultivating species such as CL, PA, and GS, which have similarly high NCV; or AD and PP, which have the greatest densities (Tables 2 and 3).

Nevertheless, to verify this grouping, pellet behavior should be complemented with more specific studies, such as thermogravimetric analysis, which would allow more precision on energy properties (Skreiberg *et al.* 2011), or other indices created to evaluate the capacity of biomass to produce heat (Sommersacher *et al.* 2011).

CONCLUSIONS

1. During the evaluation of pellet energy properties, it was found that *Cupressus lusitanica* (CL) and *Phyllostachys aurea* (PA) are the crops with the best properties to be used as fuel, and certainly to manufacture pellets, mostly due to their high net caloric value (NCV) and low ash content. There was a high variation in the pellets' physical properties, mostly as a consequence of their moisture content (MC). Nevertheless, the majority of crops had values within the ranges reported by several authors and standards. The mechanical properties of pellets from the 12 crops present overall good durability and resistance properties, ideal for their storage and transportation.
2. The multivariate principal component analysis determined four crop groupings having similar energy or physical properties, allowing for possible material combinations. Crops such as CL, PA, and *Gynerium sagittatum* (GS) present the highest NCV; *Tectona grandis* (TG), *Sorghum bicolor* (SB), and *Saccharum officinarum* (SO) have similar forces at break; *Arundo donax* (AD) and *Pennisetum purpureum* (PP) possess the highest densities; and *Coffea arabica* (CA), *Elaeis guineensis* empty fruit bunch (EFB), and mesocarp fiber of the fruit (OPMF) have similar FVI. The species within groups can be combined to obtain raw material for uniform pellet manufacturing. However, it is necessary to verify these groupings with a study considering other parameters, such as decomposition and ignition temperature provided by thermogravimetric analysis.

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